



# Physical meaning of sensor spatial response and its parameters

VH-RODA Workshop Session:  
**Quality Control/Product Validation/Best Practices**

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# Outline

- Sensor spatial response
  - PSF (Point spread function)
  - LSF (Line spread function)
  - ESF (Edge spread function), indirect
- Parameterization (MTF and RER)
- ESF and implications
- Recommendations
- Backup
  - Acronyms
  - Literature
  - Background information



# PSF (Point spread function)

$$dn(x_{LOS}, y_{LOS}) = c E(x, y) \otimes PSF(x, y)$$

$$= c \iint E(x', y') PSF(x_{LOS} - x', y_{LOS} - y') dx' dy'$$

where  $\iint PSF(x, y) dx dy = 1$

$c$ : coeff,;

$E$ : energy from the ground

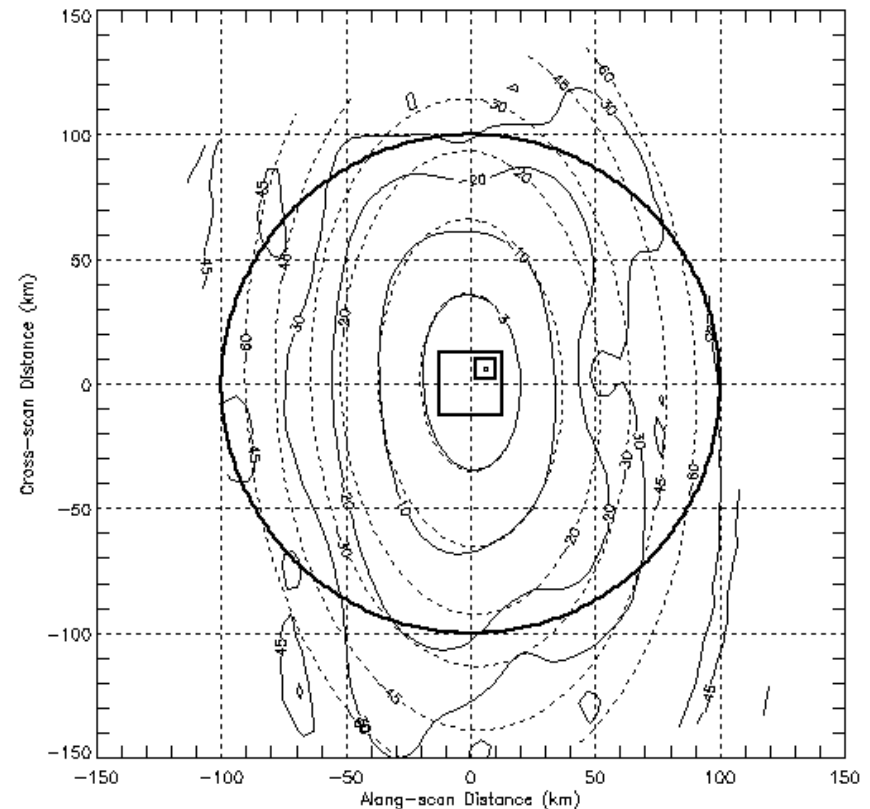
WindSat/Coriolis 6.8 GHz PSF  
(solid), Gaussian (dashed)

FWHM (-3 dB): 39 x 71 km

Squares: 1, 8, 25 km

Circle: 200 km dia.

Ground projection of an antenna pattern (dB)

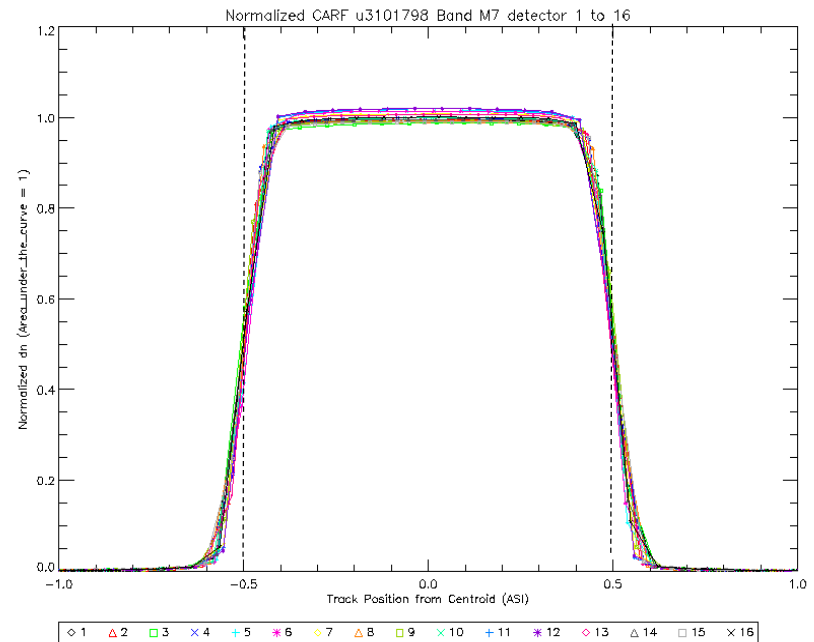
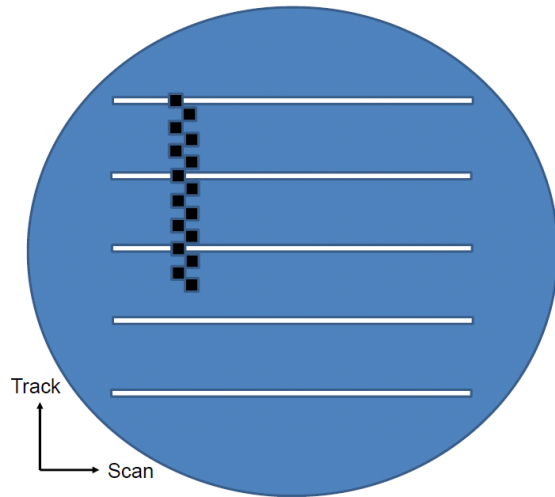


<https://www.remss.com/missions/windsat/>



# LSF (Line spread function) (1 of 2)

$$LSF(x) = LSF(x) \otimes \delta(x), \quad \delta(x) = 1 @x_0, \delta(x) = 0 \text{ elsewhere}$$



Reticles for track LSF test

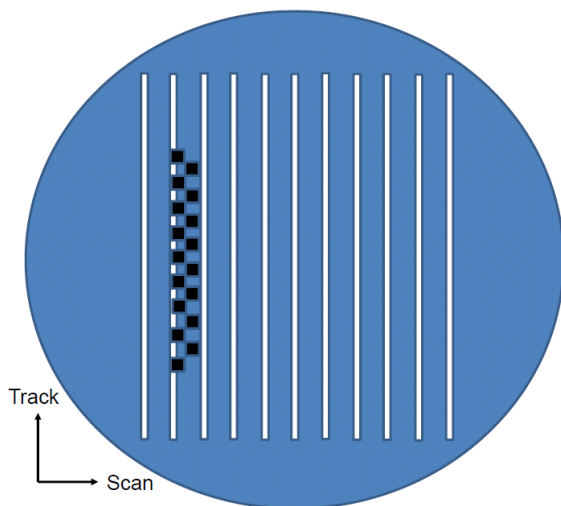
Stepping the reticle up

VIIRS Track LSFs for 16 M7 detectors



# LSF (Line spread function) (2 of 2)

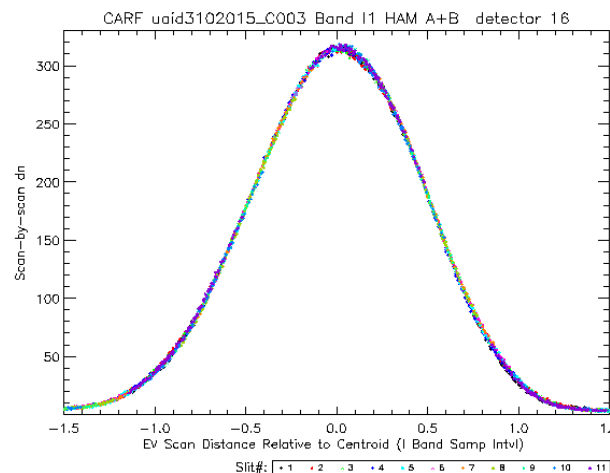
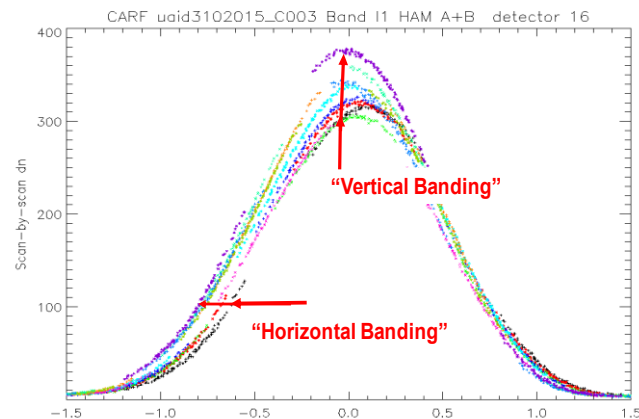
$$LSF(x) = LSF(x) \otimes \delta(x), \quad \delta(x) = 1 @x_0, \delta(x) = 0 \text{ elsewhere}$$



Reticles for scan LSF test

Scanning to the right

Spacing and throughput uniformities could become issues



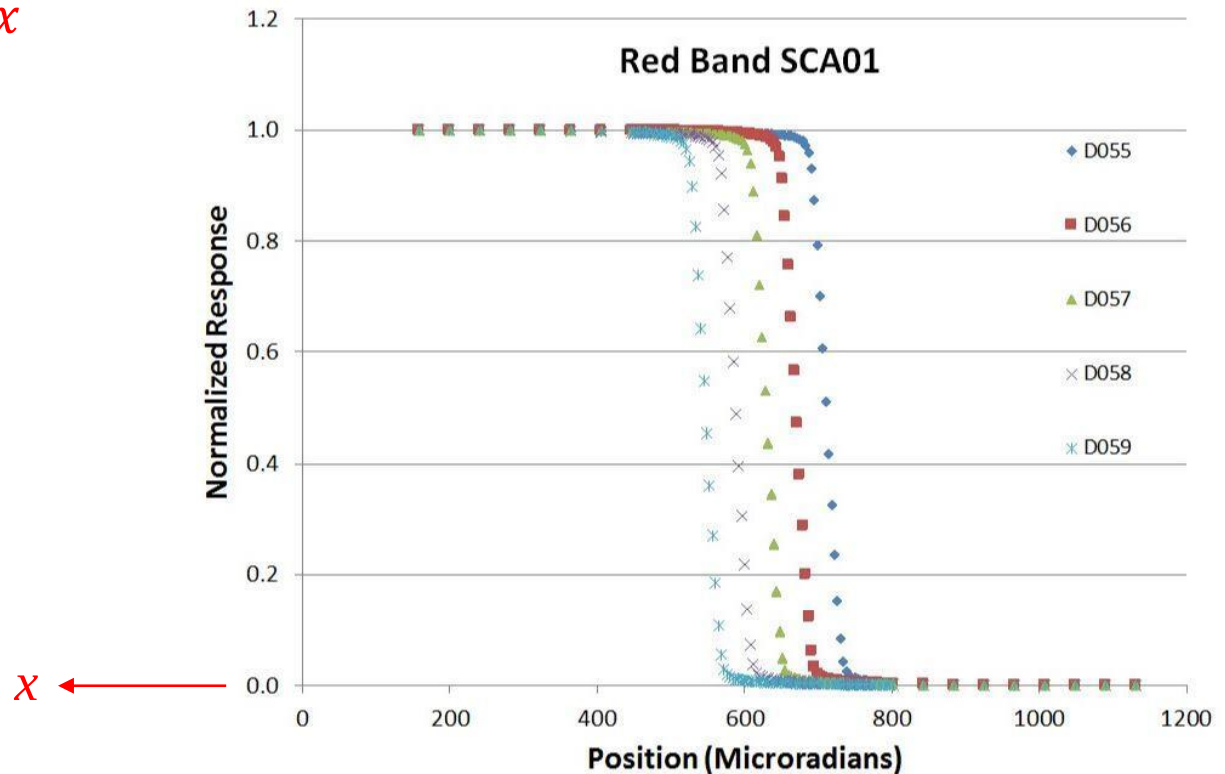
VIIRS scan direction LSF for I1 d16:  
(upper) throughput and slit phase artifacts;  
(lower) after throughput and phase corrections.



# ESF (Edge spread function)

$$ESF(x) = \int_{-\infty}^x LSF(x') dx' = LSF \otimes stepFunction$$

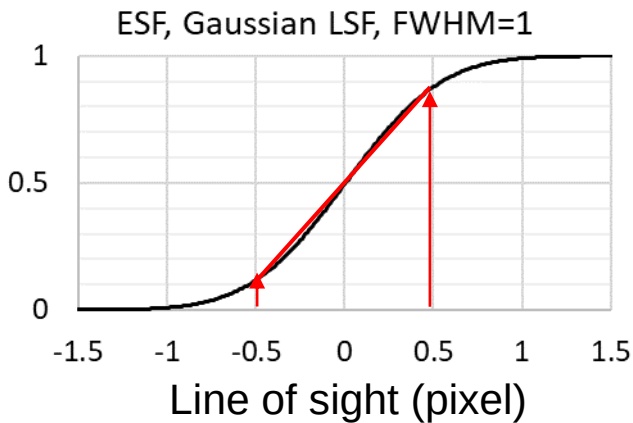
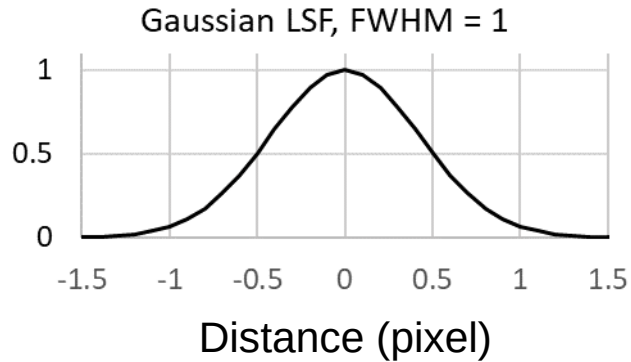
$$LSF(x) = \frac{d ESF(x)}{dx}$$



<https://www.usgs.gov/landsat-missions/spatial-performance-landsat-8-instruments>



# LSF $\rightarrow$ MTF, ESF $\rightarrow$ RER



Modulation transfer function (MTF)

$$MTF(\omega) = \frac{|FourierTransform(LSF)|}{|FourierTransform(LSF)|_{\omega=0}}$$

$\omega$  is expressed in fraction of Nyquist frequency (NF)

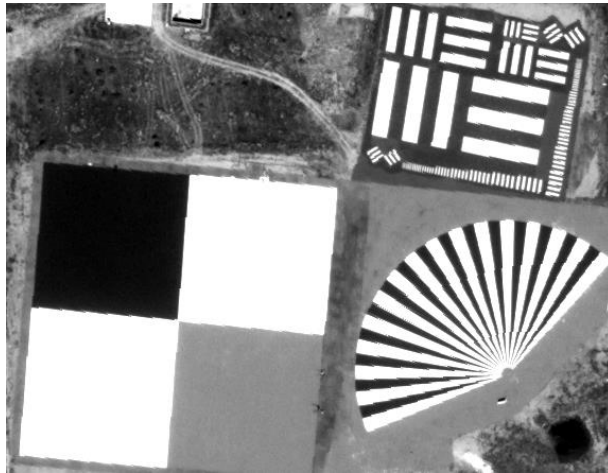
$$NF = \frac{1 \text{ cycle}}{2 \text{ sampling intervals}}$$

Relative edge response (RER)

$$RER = \frac{ESF(0.5) - ESF(-0.5)}{ESF(\infty) - ESF(-\infty)}$$



# Validation sites for very high resolution images



[https://calval.cr.usgs.gov/apps/spatialsites\\_catalog](https://calval.cr.usgs.gov/apps/spatialsites_catalog)

China site,  $40.854^{\circ}\text{N}$ ,  $109.628^{\circ}\text{E}$ .

4 48 m x 48 m slanted squares.

India site,  $17.034^{\circ}\text{N}$ ,  $78.183^{\circ}\text{E}$ .

4 70 m x 70 m slanted squares.

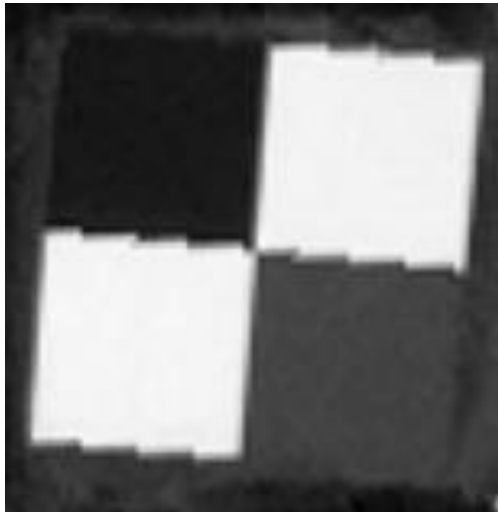
- Construct edge spread function (ESF)
- Derive line spread function (LSF)



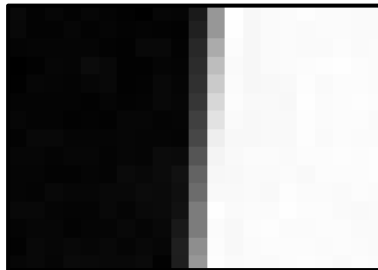
# WV3 image over China site

4 48 x 48 m squares

WV-3 (1.62 m)

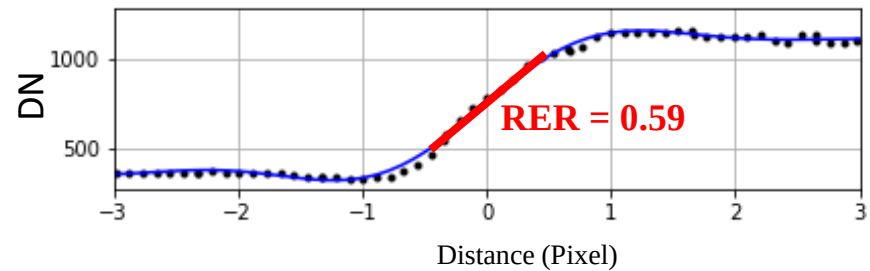


Cal/Val site: China  
Image ID: 10400100690DF600  
Band: Red

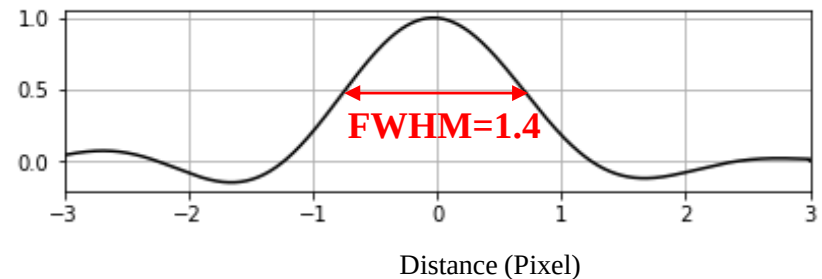


Edge used in evaluation

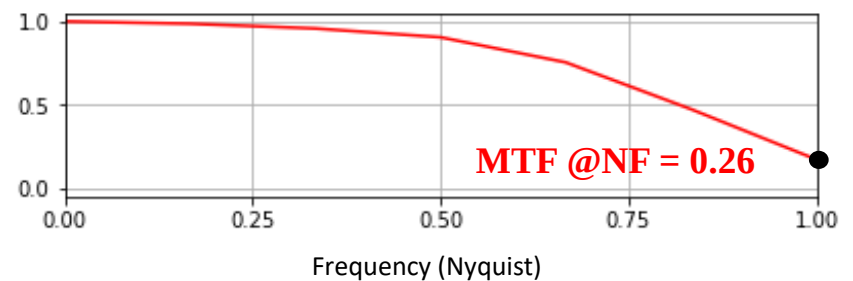
Edge Spread Function (ESF)



Line Spread Function (LSF)



Modulation Transfer Function (MTF)





# Planet image over China site

4 48 x 48 m squares

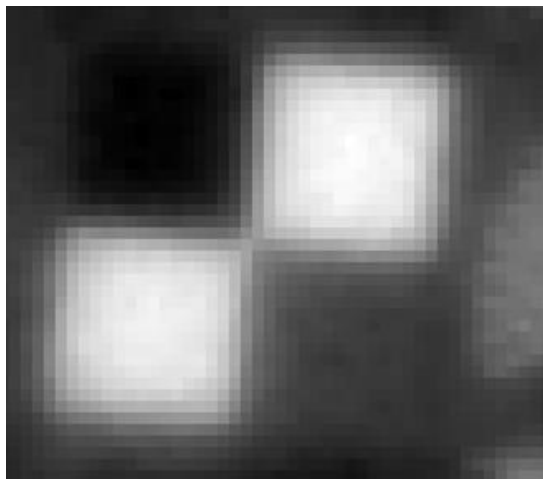
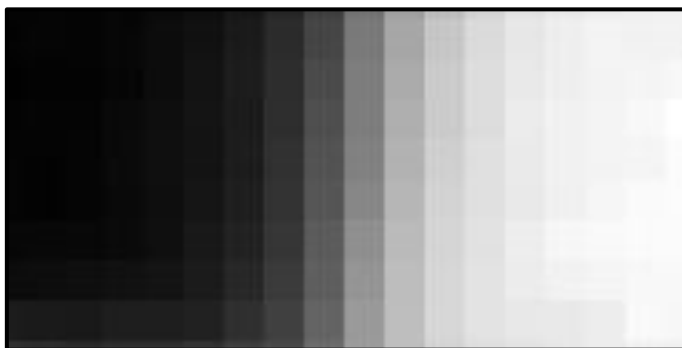


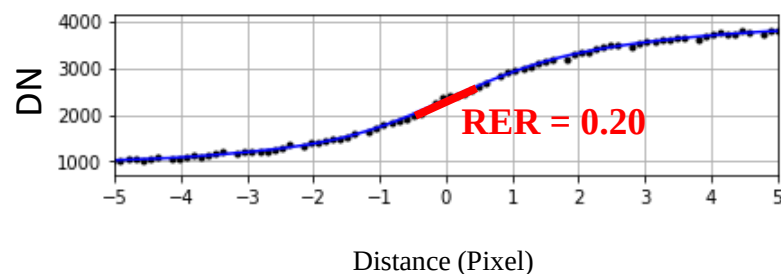
Image ID: 20221005\_031939\_43\_2254

Band: Red

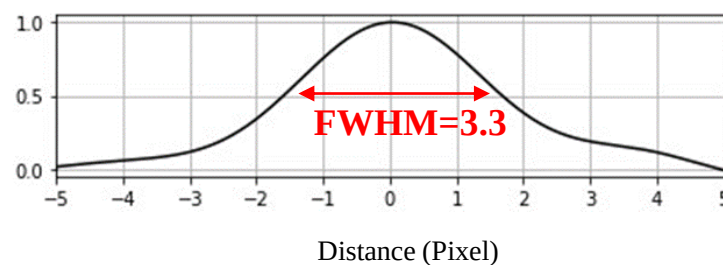


Edge used in evaluation

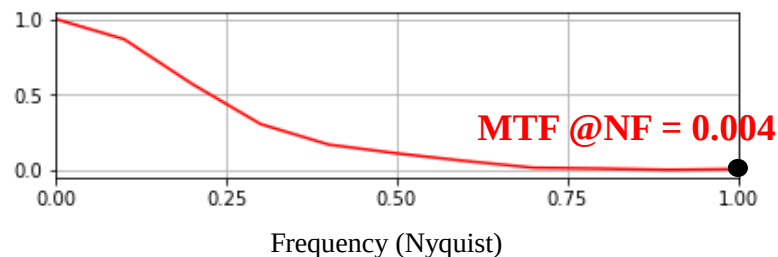
## Edge Spread Function (ESF)



## Line Spread Function (LSF)



## Modulation Transfer Function (MTF)





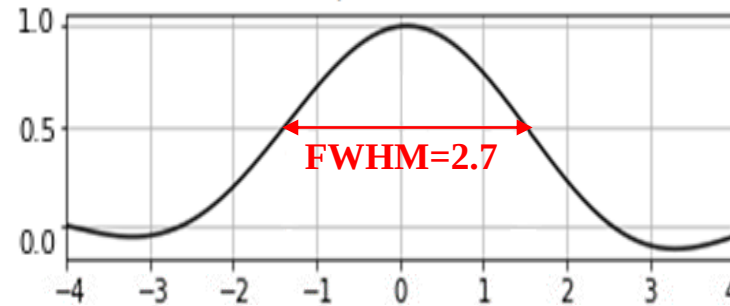
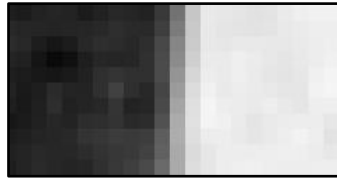
# BlackSky, Sentinel-2 Red

Sensor

Edge

LSF

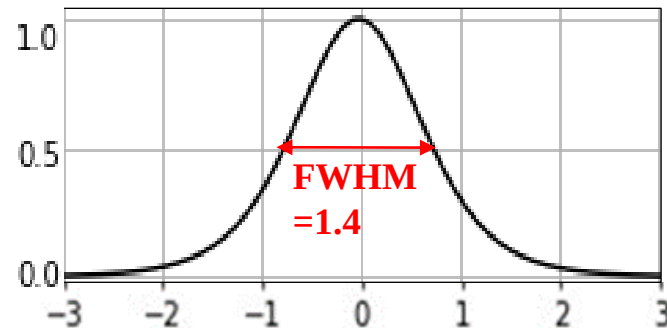
BlackSky  
Red band  
1 m pix



Sentinel-2  
Red Band  
10 m pix



India site





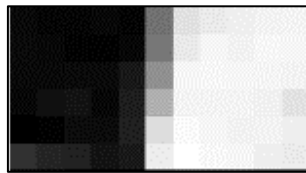
# Landsat-8 Pan, VIIRS DNB

Sensor

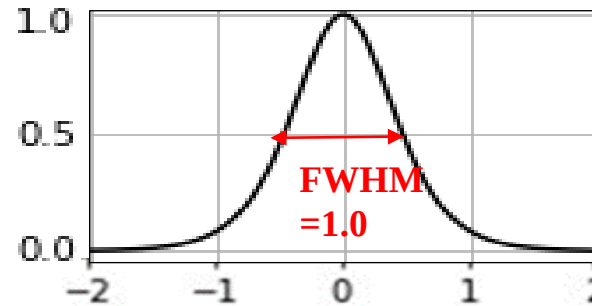
Edge

LSF

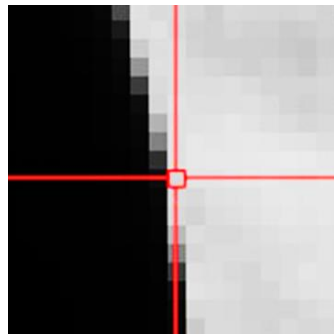
LandSat-8  
Pan band  
15m pix



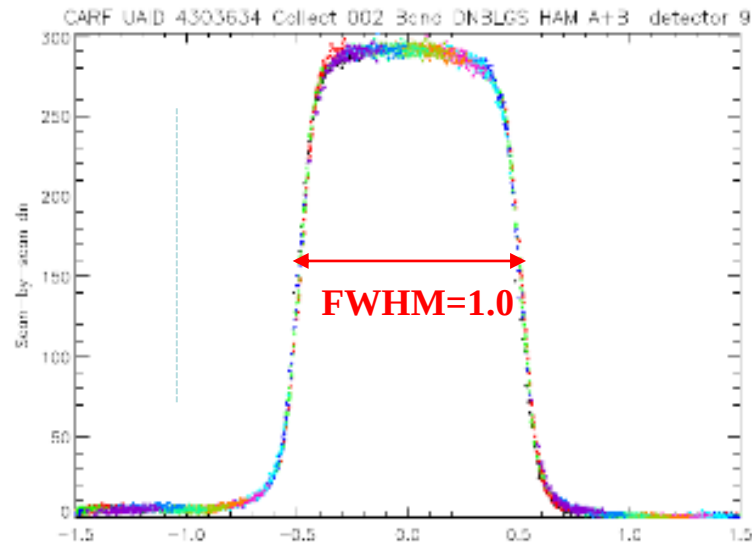
India site



VIIRS  
Day-night  
band  
750m pix



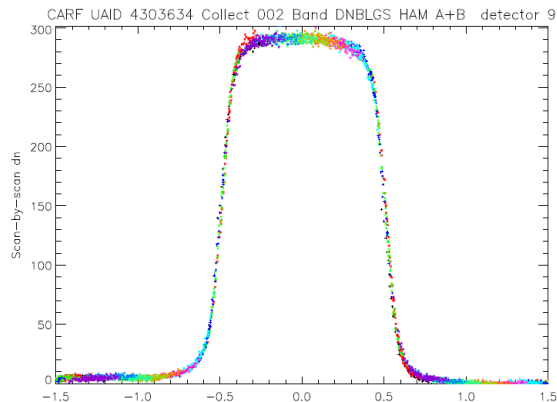
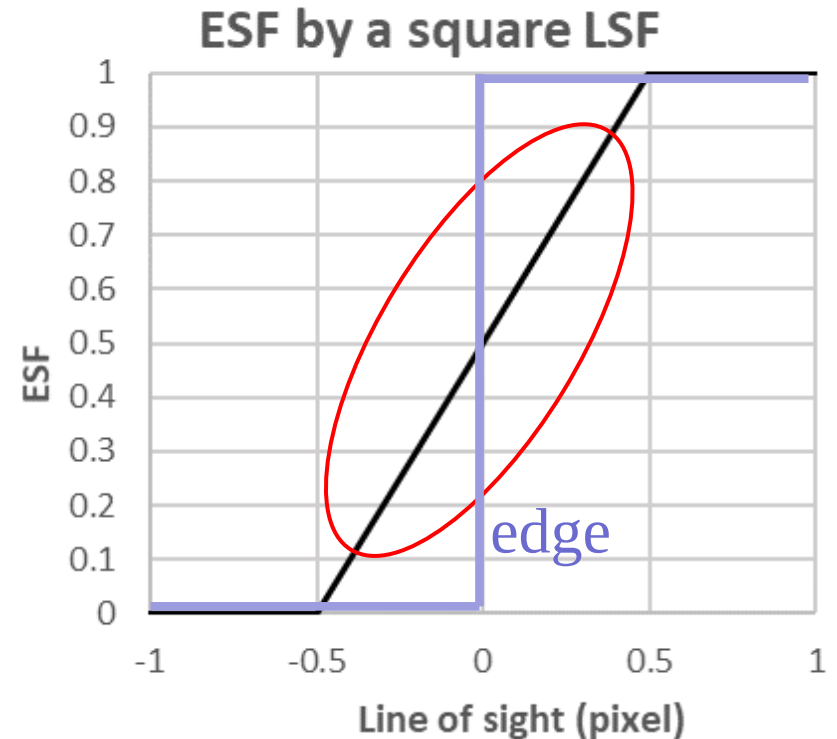
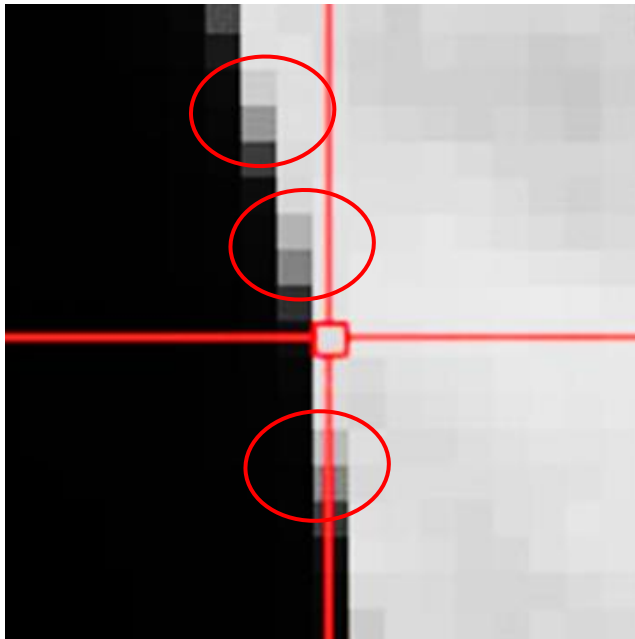
coastline





# Edge and inaccuracy

VIIRS DNB

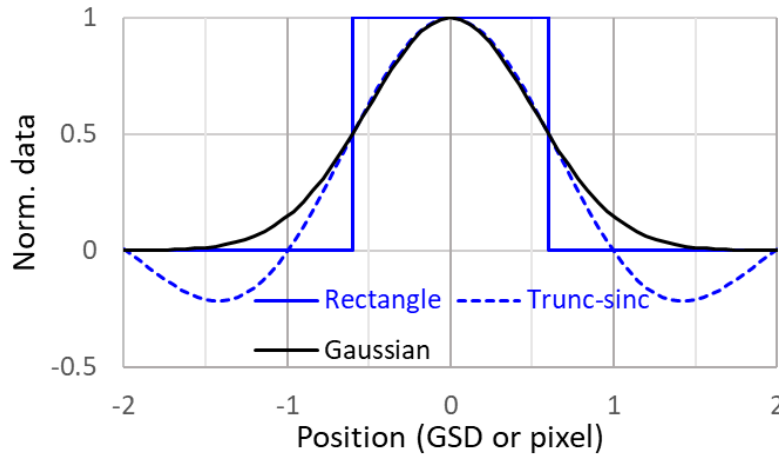


~ 80% of pixels along the edge  
has radiometric error > 10%

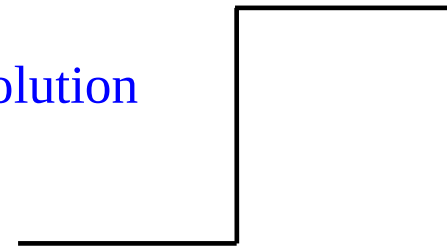


# Simulation: LSF, ESF, FWHM

3 LSFs, FWHM = 1.2 pixels



Convolution

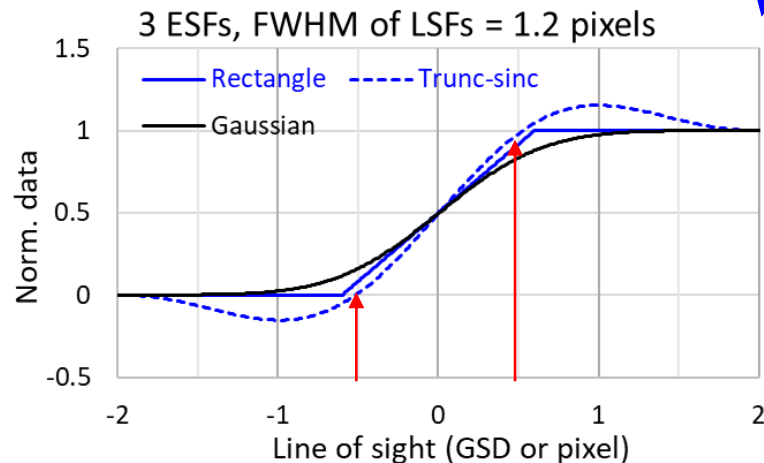


Step (edge) function

Truncated sinc function  $\frac{\sin(x)}{x}$   
is defined in  $[-2\pi, +2\pi]$

Relative edge response (RER)

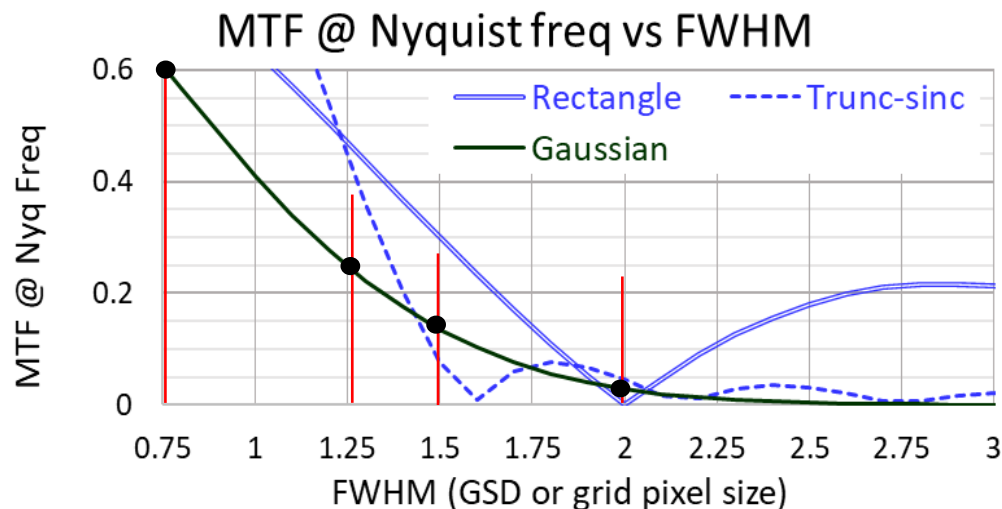
$$RER = \frac{ESF(0.5) - ESF(-0.5)}{ESF(\infty) - ESF(-\infty)}$$



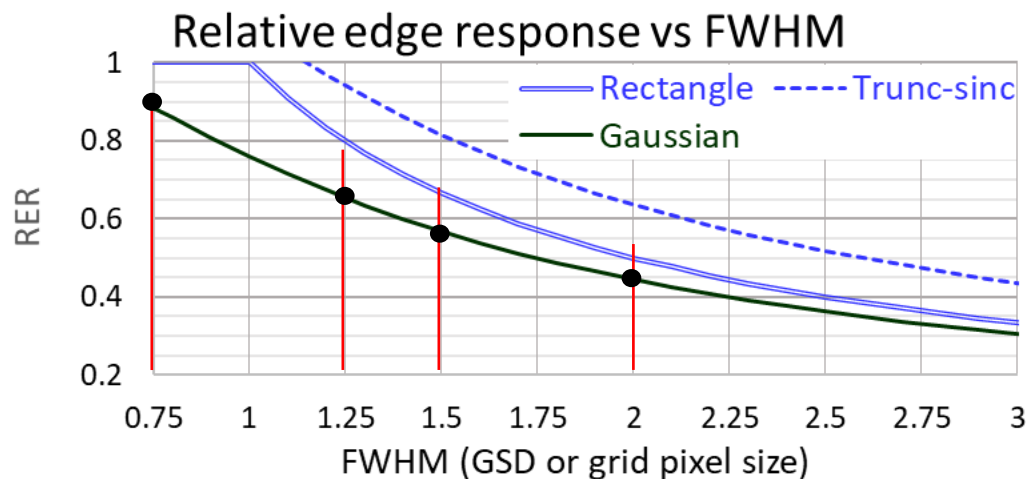
Derivative



# Simulation: MTF, RER



Gaussian function is used to set grading criteria (next chart)





# Recommendations (guidelines): FWHM, MTF, RER

- Primary parameter: FWHM to pixel-size ratio

|                  | Ideal        | Excellent   | Good       | Basic |
|------------------|--------------|-------------|------------|-------|
| FWHM/pixel ratio | (0.75, 1.25] | (1.25, 1.5] | (1.5, 2.0] | > 2.0 |

- Secondary parameters: MTF and RER based on Gaussian LSF

|        | Ideal       | Excellent    | Good         | Basic  |
|--------|-------------|--------------|--------------|--------|
| MTF@NF | [0.25, 0.6) | [0.13, 0.25) | [0.03, 0.13) | < 0.03 |
| RER    | [0.65, 0.9) | [0.55, 0.65) | [0.44, 0.55) | < 0.44 |

## Acronyms:

FWHM: full-width at half-maximum of an LSF

LSF: sensor system line spread function

MTF: modulation transfer function

NF: Nyquist frequency

RER: relative edge response

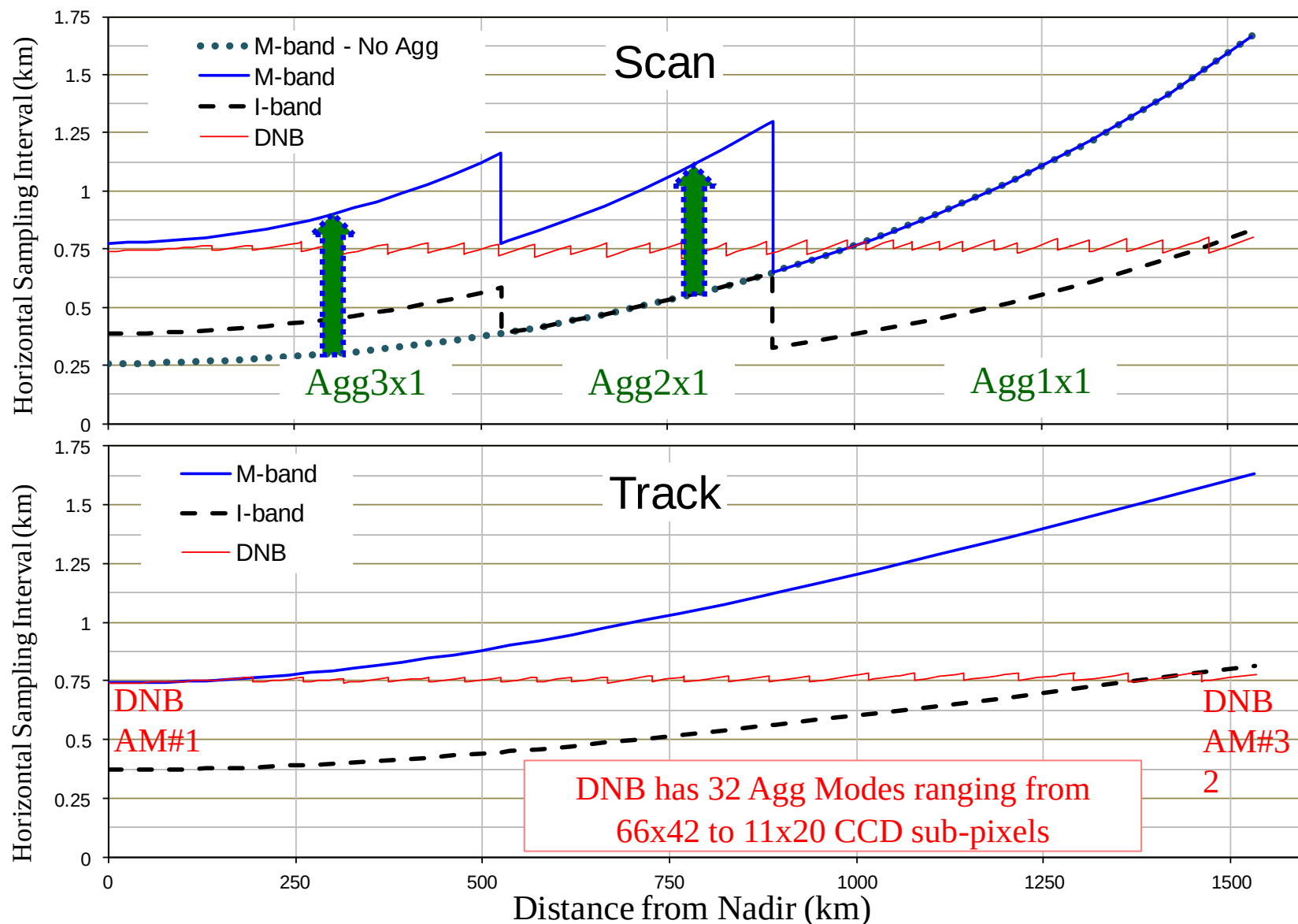
DRAFT



Earth Observation Mission Quality  
Assessment Framework - Optical Guidelines



# Improvements by aggregation (VIIRS)





# Backup slides



# Acronyms of example sensor, **satellites**

- AVHRR: Advanced Very-High-Resolution Radiometer
- OLS: Operational Linescan System
- VIIRS: Visible Infrared Imaging Radiometer Suite
- ABI: Advanced Baseline Imager
- NPOESS: National Polar-Orbiting Operational Environmental Satellite System
- NPP: NPOESS Preparatory Project
- SNPP: Suomi National Polar-orbiting Partnership (Suomi NPP) = NPP renamed after launch
- JPSS: Joint Polar Satellite System (J1 = NOAA-20, J2 = N21 after launch, J3 & J4 to be launched ~ 2032, 2027)
- GOES-R: Geostationary Operational Environmental Satellites-R series (-R/16/East, -S/17/Storage, -T/18/West, -T to be launched mid-2024)

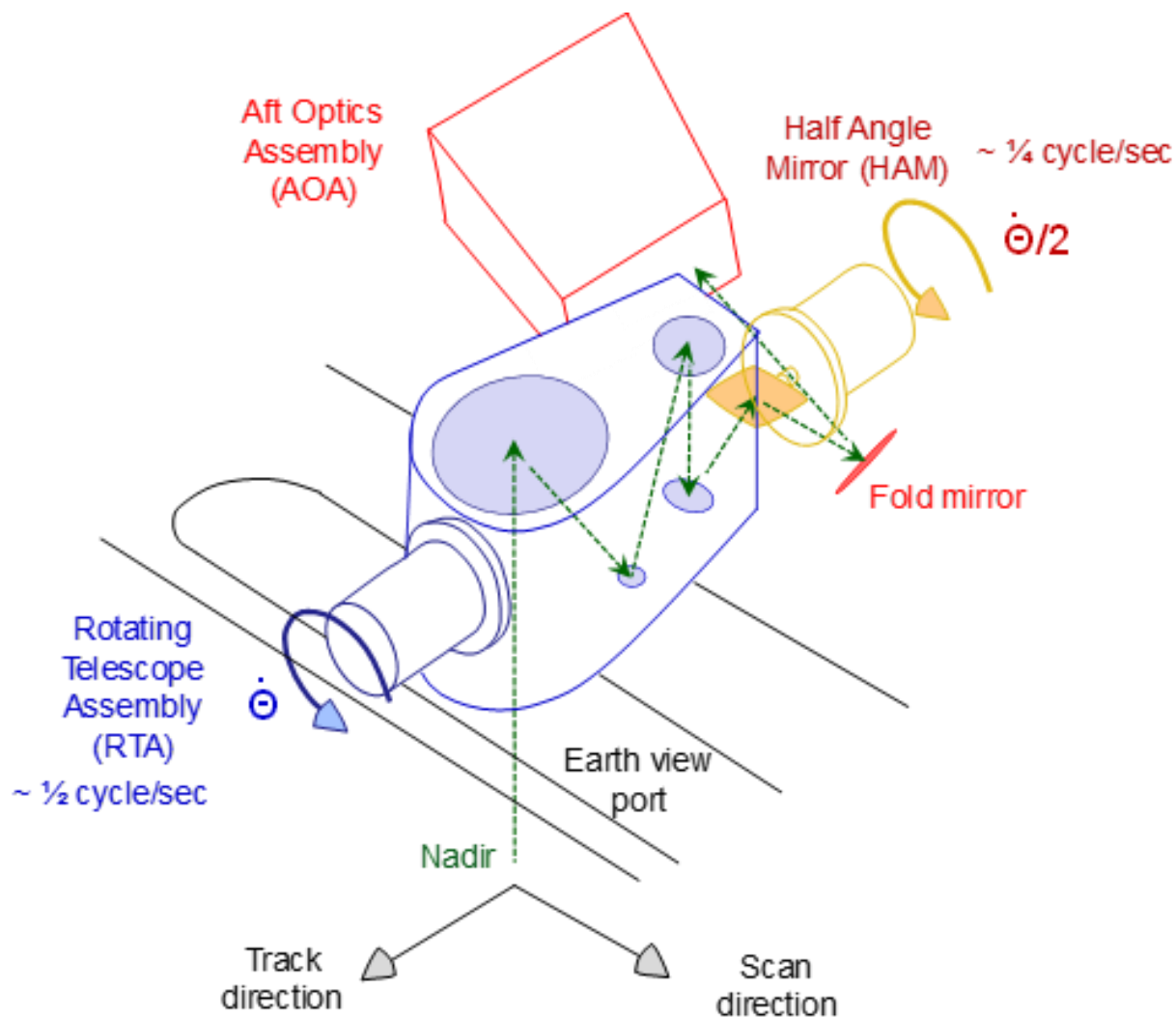


# References

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- Lin, G., R. E. Wolfe, M. Nishihama, 2011, "NPP VIIRS Geometric Performance Status", Earth Observing Systems XVI, edited by James J. Butler, Xiaoxiong Xiong, Xingfa Gu, Proc. of SPIE Vol. 8153, 81531V, doi: 10.1117/12.894652.
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- NOAA, 2019, GOES R SERIES PRODUCT DEFINITION AND USERS' GUIDE <https://www.goes-r.gov/users/docs/PUG-L1b-vol3.pdf>
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# VIIRS instrument characteristics



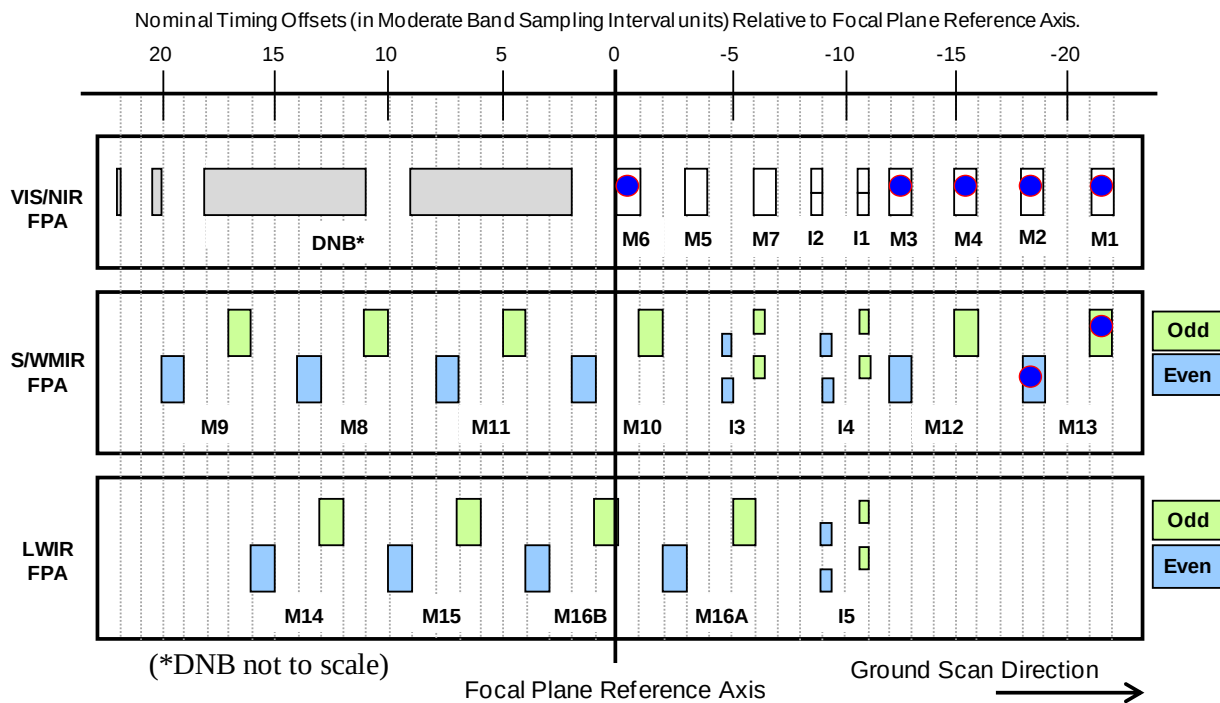
**VIIRS 22 Bands:**  
16 M-Band, 5 I-Band and 1 DNB

| VIIRS Band | Spectral Range (um) | Nadir GSD (m) |
|------------|---------------------|---------------|
| DNB        | 0.500 - 0.900       | 750           |
| M1         | 0.402 - 0.422       | 750           |
| M2         | 0.436 - 0.454       | 750           |
| M3         | 0.478 - 0.498       | 750           |
| M4         | 0.545 - 0.565       | 750           |
| I1         | 0.600 - 0.680       | 375           |
| M5         | 0.662 - 0.682       | 750           |
| M6         | 0.739 - 0.754       | 750           |
| I2         | 0.846 - 0.885       | 375           |
| M7         | 0.846 - 0.885       | 750           |
| M8         | 1.230 - 1.250       | 750           |
| M9         | 1.371 - 1.386       | 750           |
| I3         | 1.580 - 1.640       | 375           |
| M10        | 1.580 - 1.640       | 750           |
| M11        | 2.225 - 2.275       | 750           |
| I4         | 3.550 - 3.930       | 375           |
| M12        | 3.660 - 3.840       | 750           |
| M13        | 3.973 - 4.128       | 750           |
| M14        | 8.400 - 8.700       | 750           |
| M15        | 10.263 - 11.263     | 750           |
| I5         | 10.500 - 12.400     | 375           |
| M16        | 11.538 - 12.488     | 750           |

○ Dual gain band



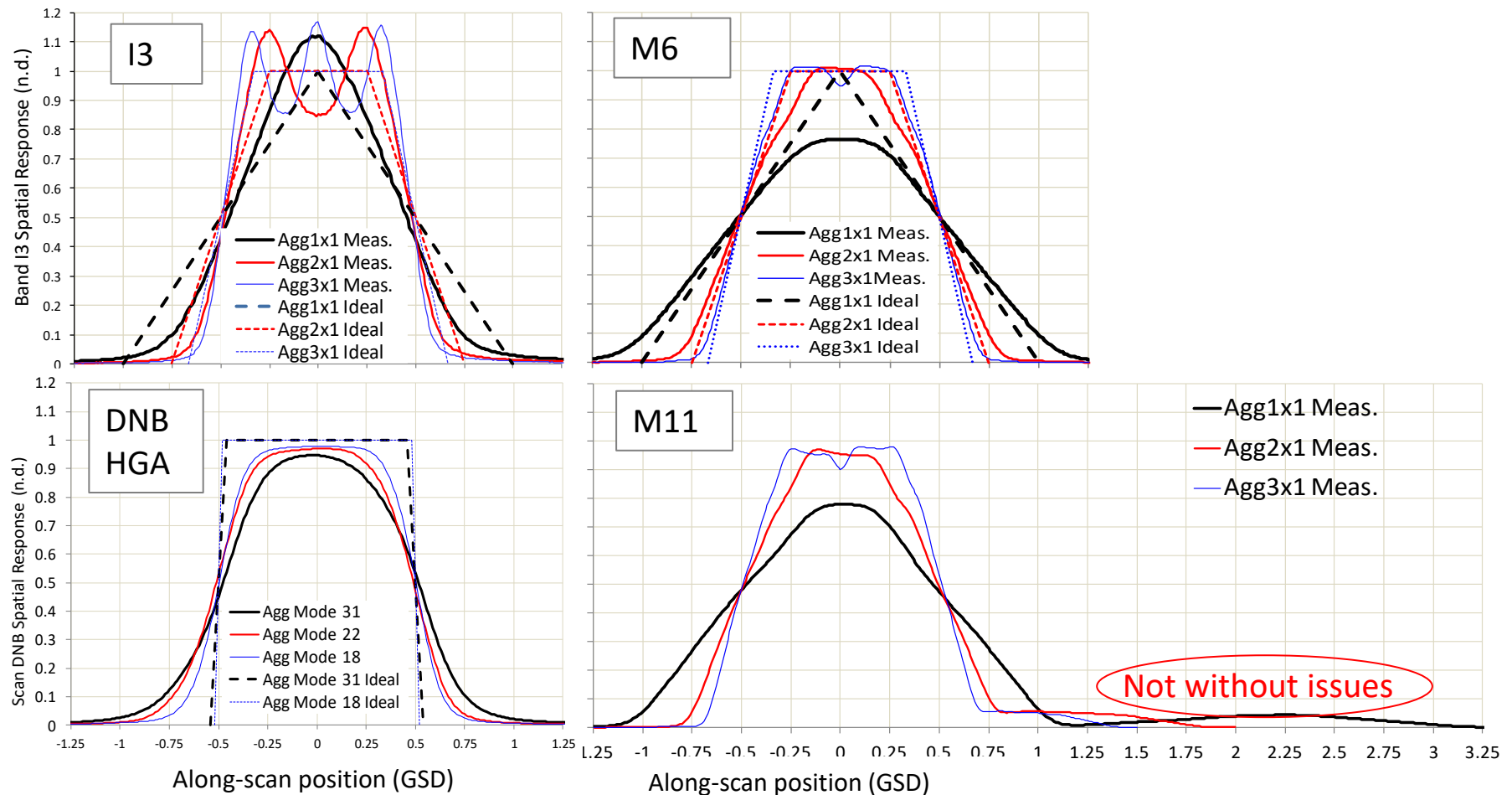
# VIIRS band layout



● Dual gain band



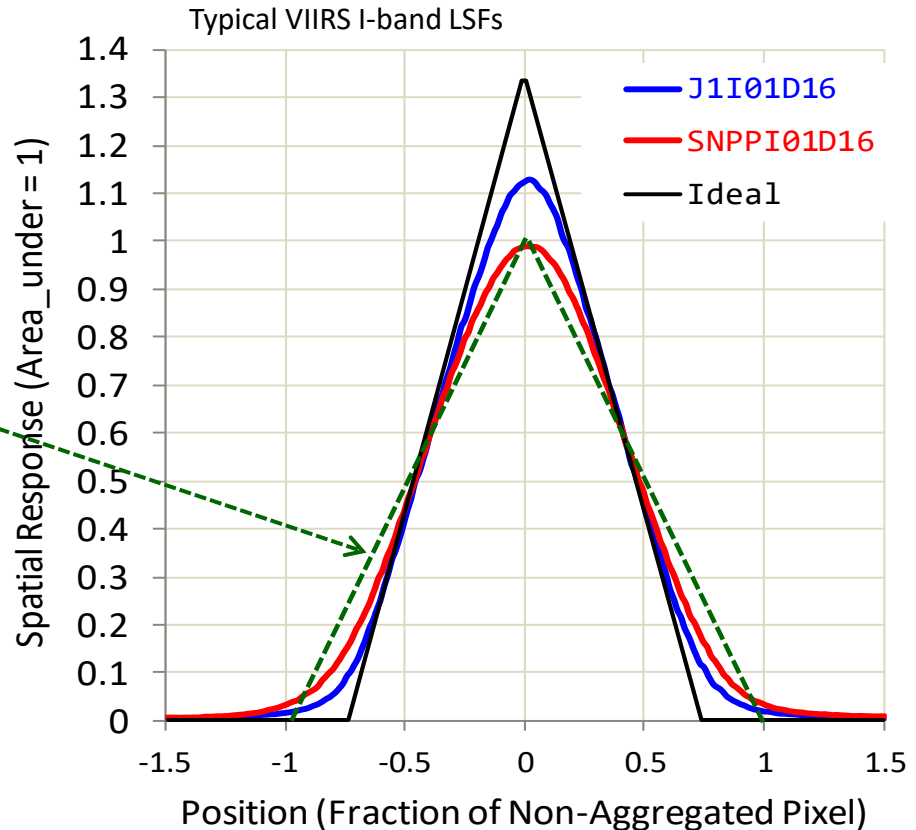
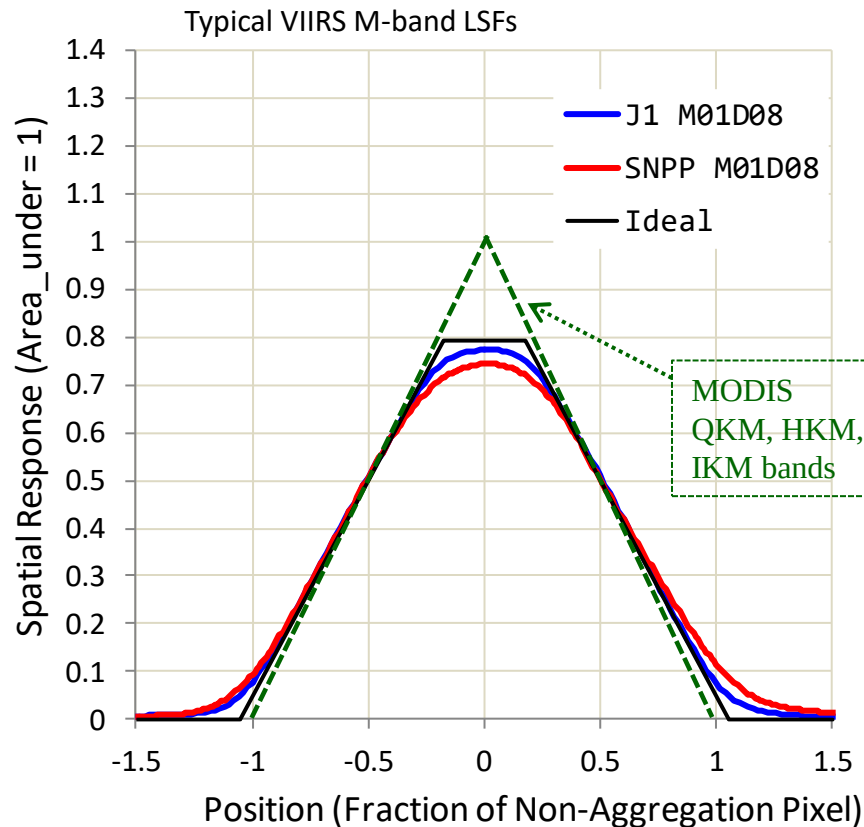
# Typical SNPP VIIRS scan direction LSFs



- Aggregation makes LSFs more square
- DNB LSFs are nearly square
- LSFs in the track direction are mostly squares (not shown here)



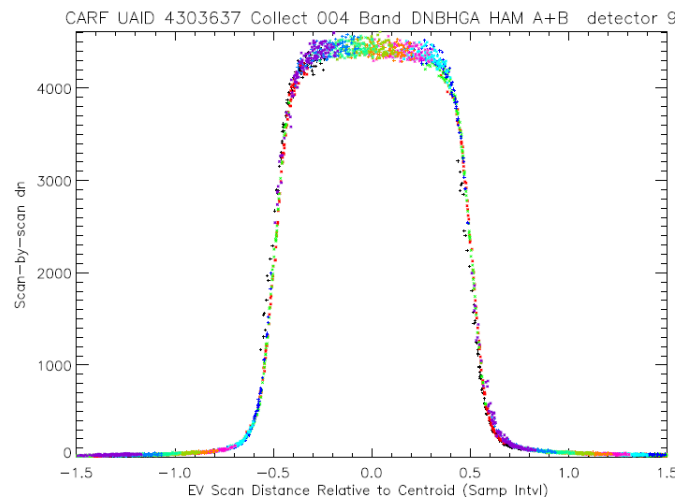
# Optical calibration



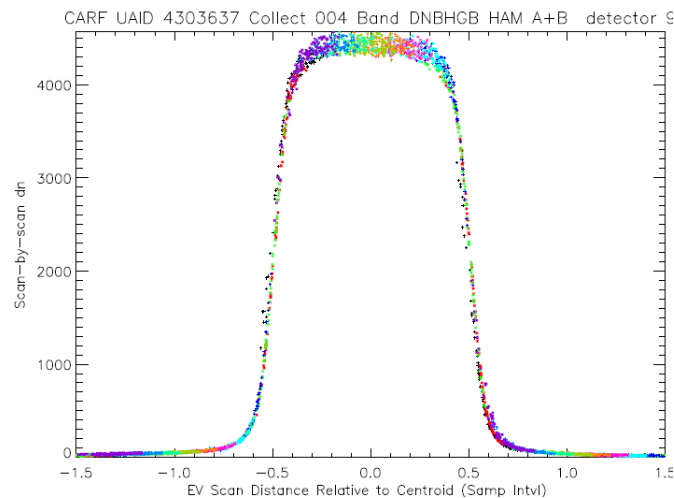
- J1 VIIRS has improved optical system over SNPP
- J2, J3, J4  $\sim$  J1



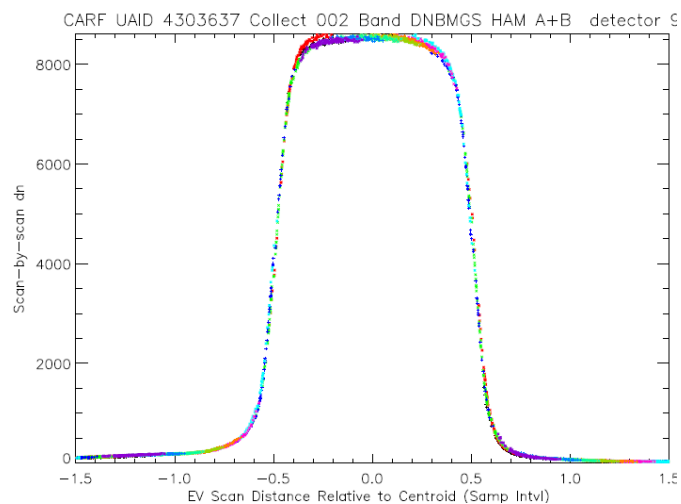
# J1 VIIRS DNB along-scan LSFs



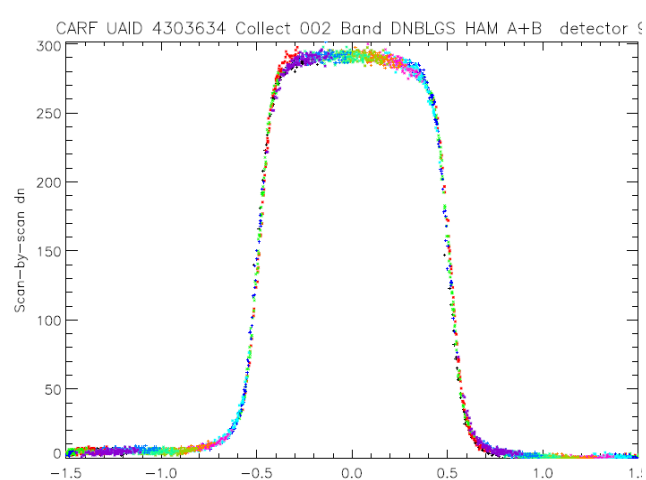
(a) HGA



(b) HGB



(c) MGS

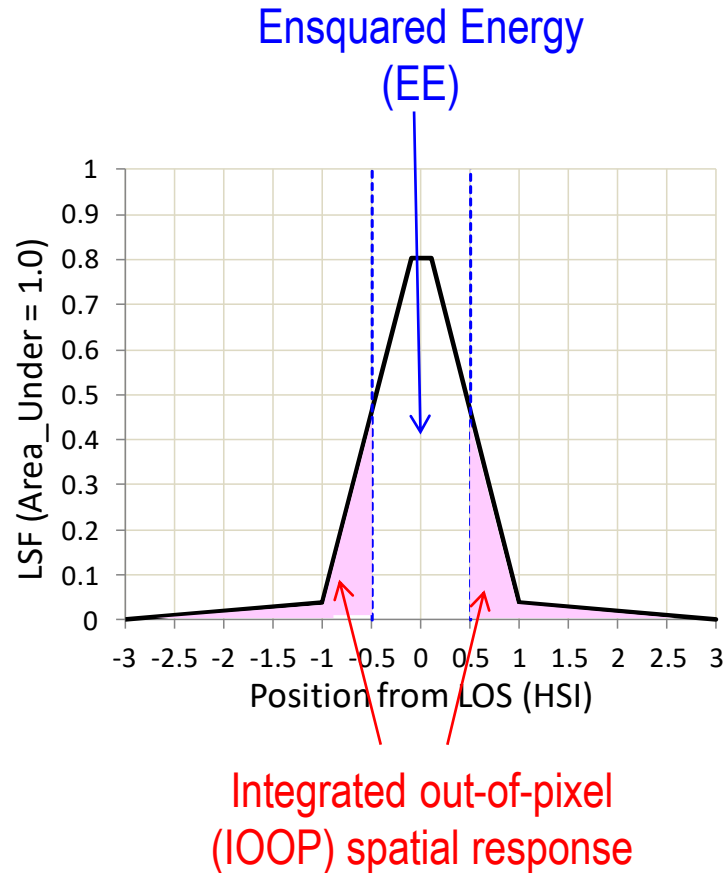


(d) LGS

Fig. 12. LSFs in the scan direction for the 4 gain stages in aggregation mode 18.



# MTF, EE & IOOP



$$MTF(\omega) = \frac{|FourierTansform(LSF)|}{|FourierTansform(LSF)|_{\omega=0}}$$

$\omega$  is expressed in fraction of Nyquist frequency  
(maximal detectible sinusoidal waves)

$$f_{Nyquist} = \left( \frac{1}{2HSI} \right)$$

$$EE = \int_{|x| \leq \frac{1}{2}} LSF(x) dx$$

$$\begin{aligned} IOOP &= \int_{|x| > \frac{1}{2}} LSF(x) dx \\ &= 1 - EE \end{aligned}$$

- “IOOP” is the weight outside the sampled pixel ( $\frac{1}{2} \pm$  pixels), a term borrowed from integrated out-of-band (IOOB) response in spectral characterization



# GOES-R ABI & JPSS VIIRS MTF Spec

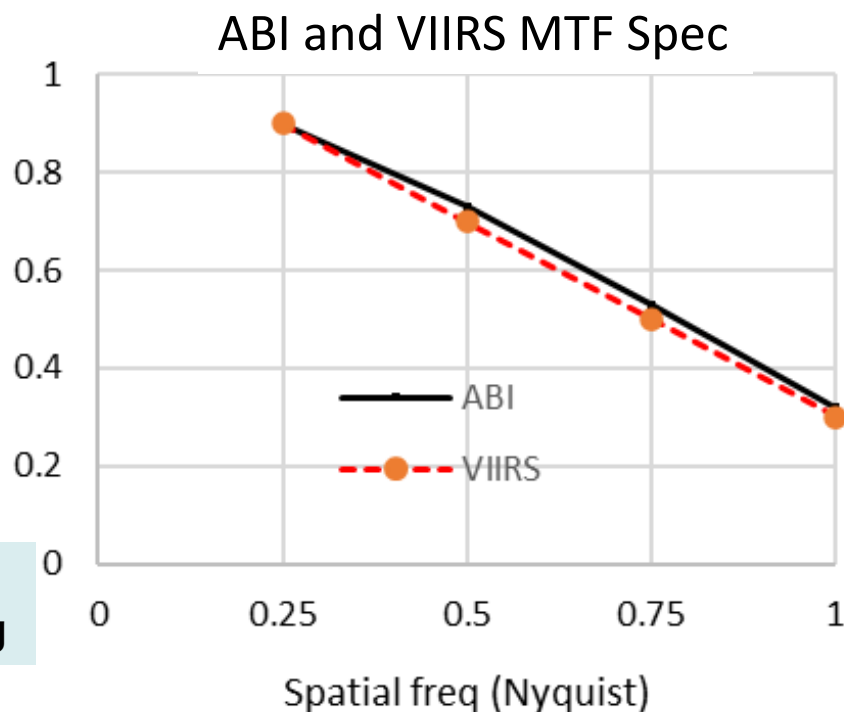
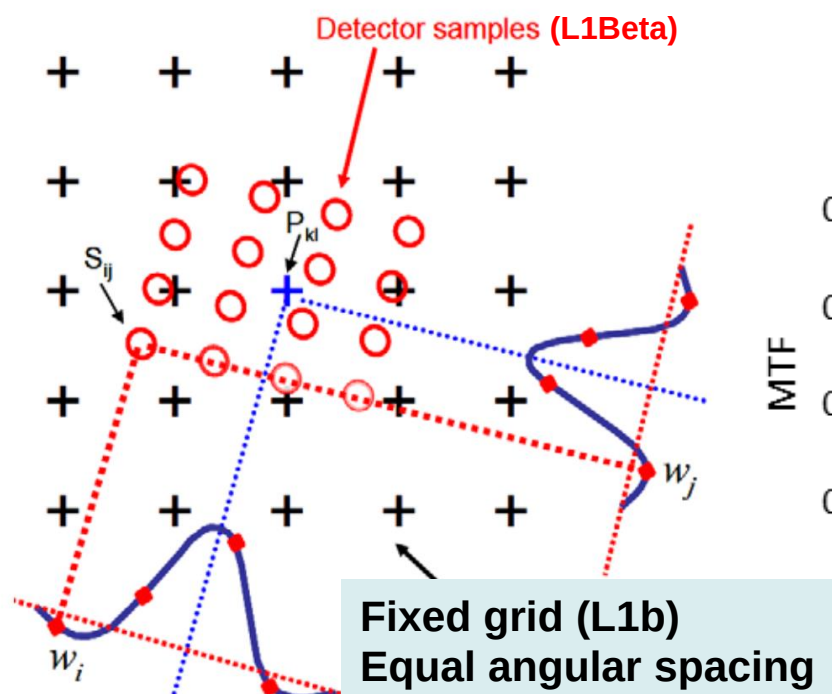


Figure 5.1.3.5 ABI Level 1b Resampling Process

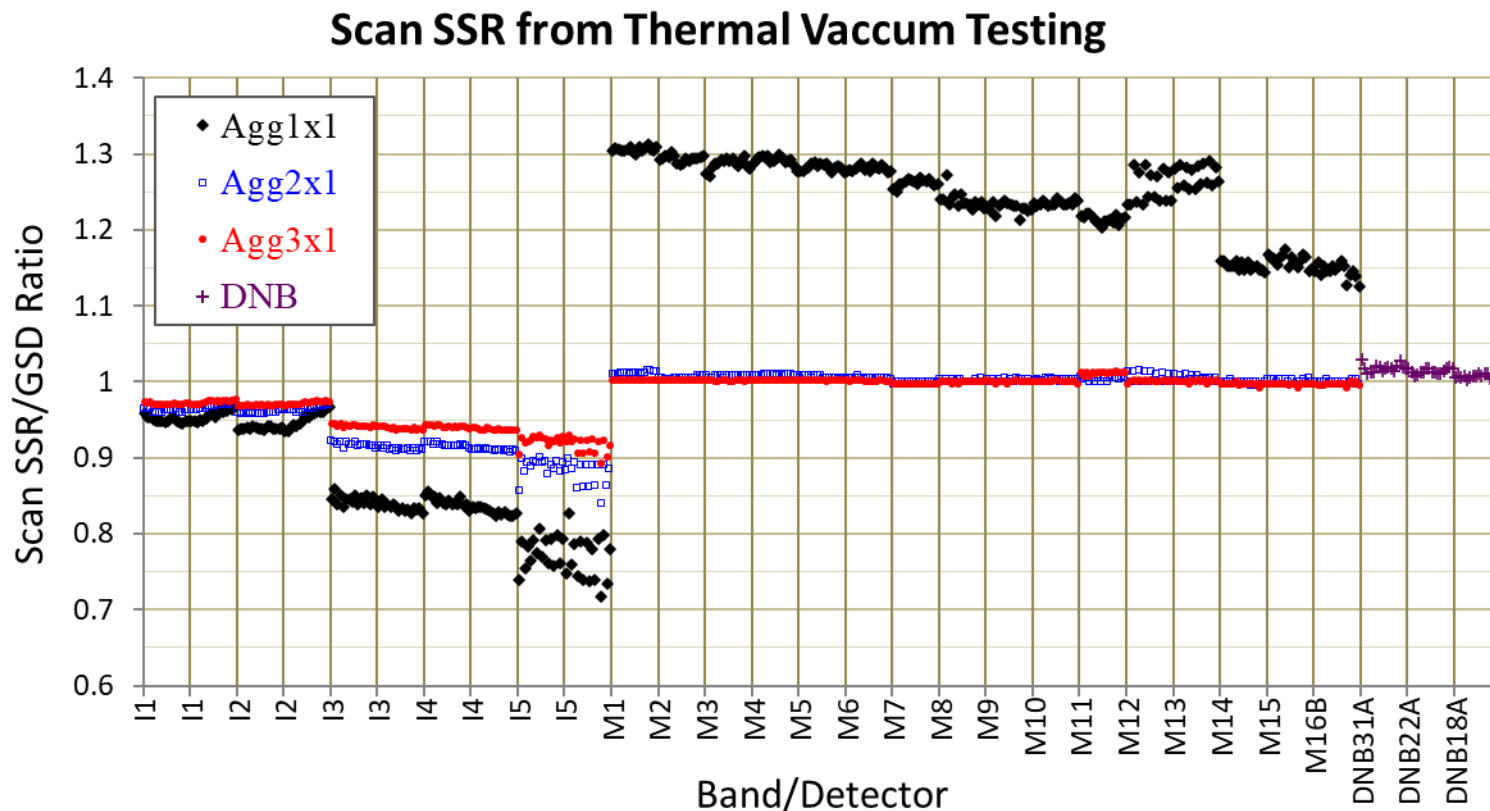
<https://www.goes-r.gov/users/docs/PUG-L1b-vol3.pdf>

Truncated sinc function  $\frac{\sin(x)}{x}$   
in  $[-2\pi, +2\pi]$  is used as kernels

M. Cook et al, "A Pathway to Optimize GOES-R ABI Hot Spot Detection and Fire Monitoring using ABI L1Beta Imagery", AMS Annual Meeting, 1/28 - 2/2, 2024, Baltimore, MD



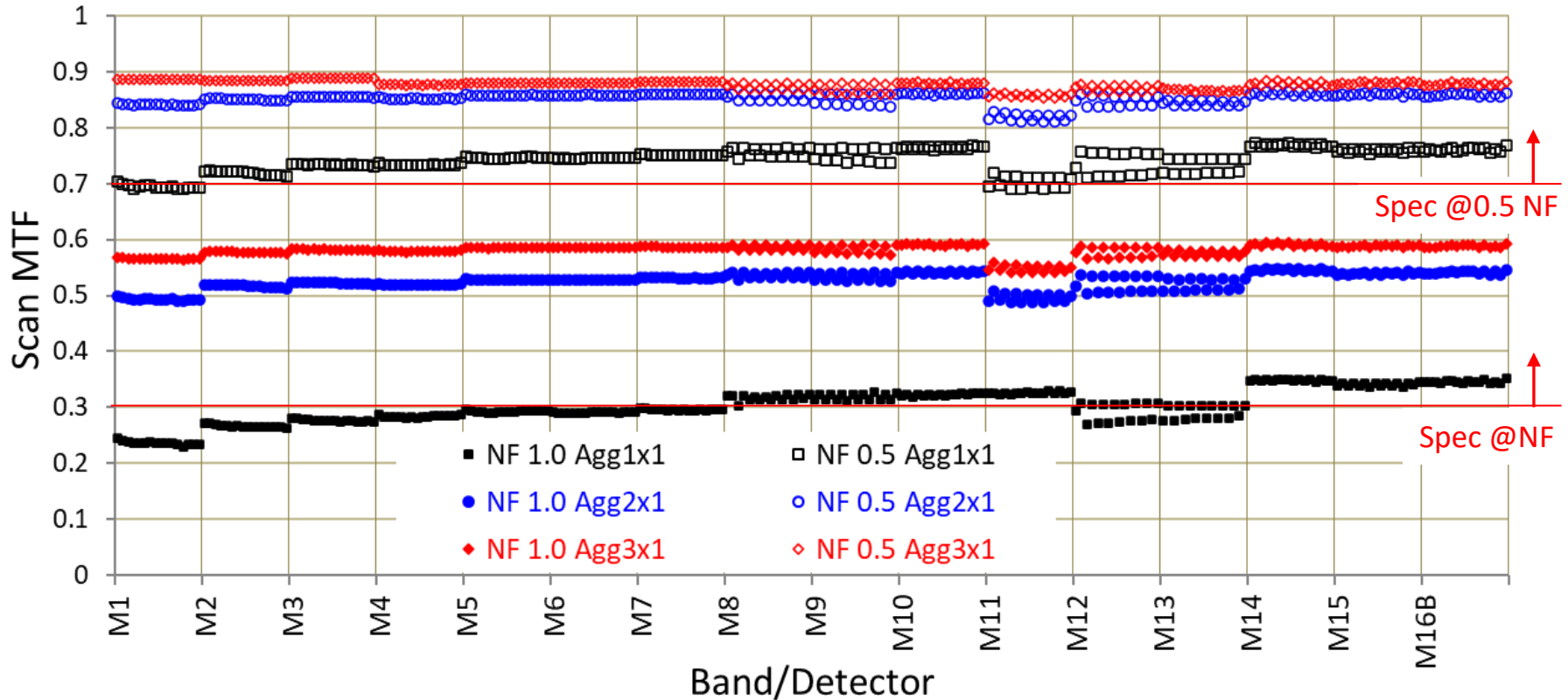
# SNPP VIIRS SSR in scan direction



- SSR (sensor spatial resolution) = FWHM of an LSF
- I-bands under-sample in all aggregation zones
- M-bands oversample in Agg1x1 zones
- DNB and M-bands in Agg2x1 & 3x1 zones sample at “Nyquist”



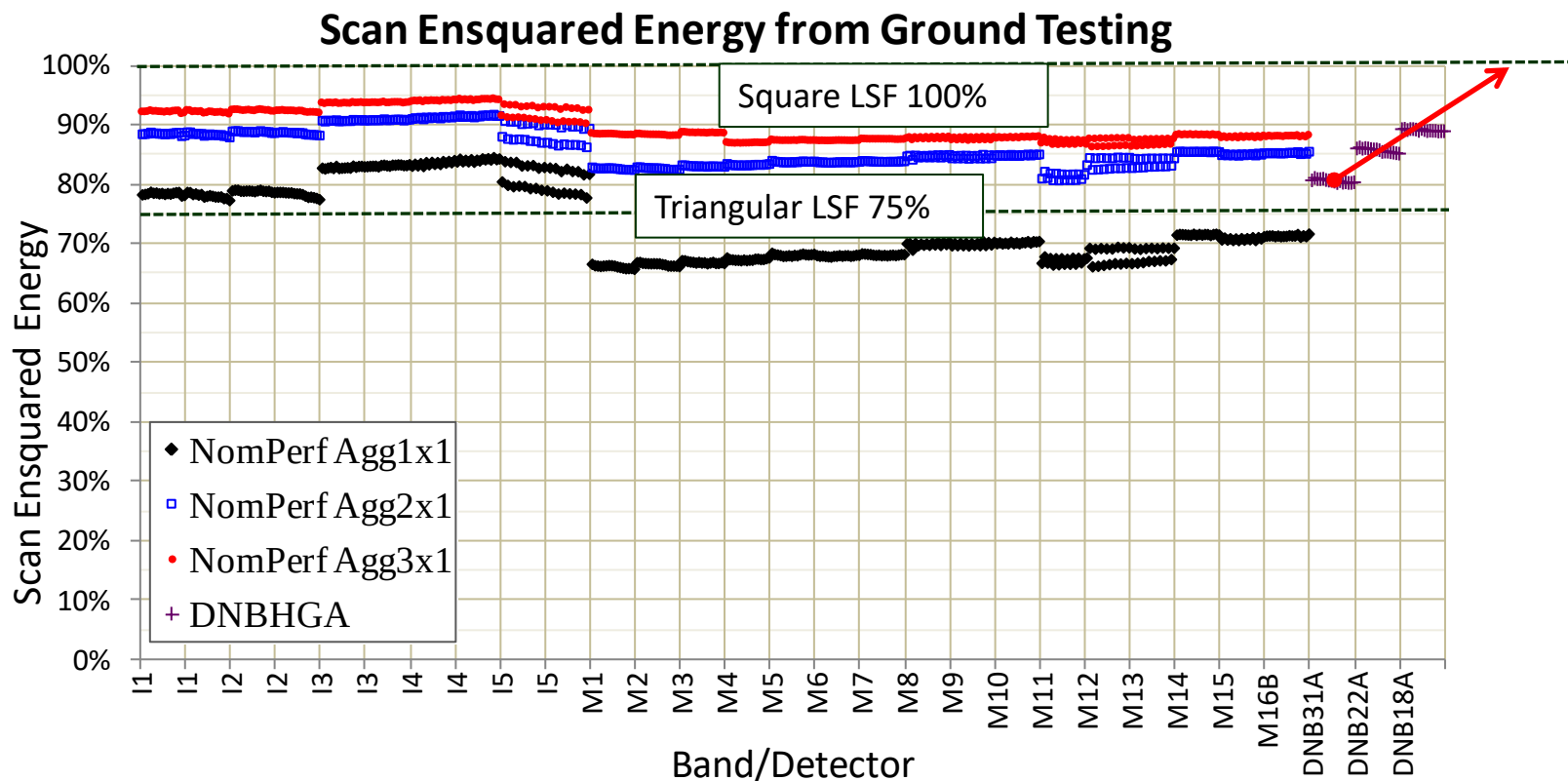
# SNPP VIIRS MTF in scan direction



- MTF improves as more samples are aggregated
- Waivers were approved for spec non-compliance in some bands



# Ensquared energy (EE)



- I-bands collect more energy within sampled pixels (TOA) than those by M-bands
- DNB tends to collect 100% energy within the sampled pixel in the nadir Agg Modes